Bose-Einstein Correlations at the Electron-Ion Collider[1]

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Two of the scientific goals of the EIC are to (1) unravel the properties of high-density nuclear matter and (2) understand how QCD forms hadrons from the underlying quarks and gluons in hard scattering (fragmentation and hadronization) [1]. To achieve these goals we propose to take advantage of an iconic quantum mechanical effect; the symmetrization of the wave function required for bosons in quantum mechanics. Particles formed near one another will have overlapping wave functions and the interference of the wave functions produces correlations in the intensity and momentum dependence of the final particles. These Bose-Einstein Correlations (BEC) (or the Hanbury-Brown Twiss effect) are examples of intensity interferometry and can be used to study the space-time extent of the source of the particles and/or learn about the dynamics of their formation. In this section we will discuss the background of BEC measurements relevant to measurements at the EIC and the status of previous measurements. We will also discuss our current understanding of high-density nuclear matter and hadronization and current limits to that understanding. We will then present results from simulations of BECs at EIC kinematics to gain a firmer understanding of what we may learn with the EIC.

The origin of Bose-Einstein Correlations lies in the fact that when two identical bosons are detected, their joint wave function $|p_1 p_2\rangle$ (p_i is the particle 4-momentum) must be symmetric under particle exchange. In other words, when the two bosons are detected from different points in space-time, the observer cannot distinguish the origin of each particle so their amplitudes must add. This requirement gives rise to interference terms in the intensity that do not exist for non-identical particles or for fermions. In fact, for fermions there is an anti-correlation between the particles. The BEC in energy-momentum space is related to the extent of the source in its spatial dimensions and the correlation function can be written as

$$R(Q_{12}, r_{12}) = \frac{dN/dQ_{12}}{dN_{ref}/dQ_{12}} \tag{1}$$

where $Q_{12} = \sqrt{-(p_1 - p_2)^2}$ is the Lorentz-invariant momentum difference between the identical bosons, r_{12} represents the size of the emission source and N_{ref} is a reference spectrum constructed with no BECs. The correlation function is often parameterized at

$$R(Q_{12}, r_{12}) = \alpha\left(1 + \lambda\Omega(Q_{12}r_{12})\right)\left(1 + \beta Q_{12}\right). \tag{2}$$

In static models of particle sources $\Omega(Q_{12}r_{12})$ can be interpreted as the Fourier transform of the spatial distribution of the emission region of bosons with overlapping wave functions and is characterized by the size parameter r_{12}. It is typically treated as a Gaussian ($e^{-Q_{12}^2 r_{12}^2}$) or an exponential ($e^{-Q_{12}r_{12}}$). The parameter λ measures the coherence of the source, α is a normalization factor, and β accounts for long range correlations.

We now consider some examples of BECs. There is a long history of the study of BECs in particle and nuclear physics going back to 1960 when they were measured in $p\bar{p}$ collisions [2]. They have been used to study geometric properties in ep reactions[3], the space-time extent of hot nuclear matter in Au-Au collisions [4, 5], and the dynamical properties of hadrons extracted from Au-Au collisions [6]. Figure 1 shows the two-pion correlation function from the Ref. [3] for ep reactions measured at the DESY collider for an electron momentum $p_e = 27.6$ GeV and proton momenta $p_p = -820$ GeV and $p_p = -920$ GeV. It shows several of the important features seen in many correlation functions. There is a clear correlation that is a maximum at $Q_{12} = 0$ and drops rapidly to unity and below with increasing momentum difference. The height of the correlation function at $Q_{12} = 0$ measures the coherence in the source. At moderate Q_{12} the correlation drops below one reflecting the usual practice of requiring the integral of the entire correlation function to go to one. There is a steady rise in R at larger Q_{12}. Recall the denominator Eq. 1. It should be free of the correlations

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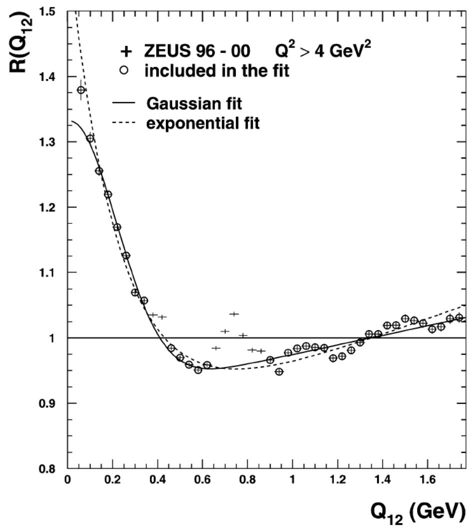

Figure 1: The measured Bose-Einstein correlation function, $R(Q_{12})$, together with Gaussian and exponential fits [3]. The error bars show the statistical uncertainties. The data points included in the fit are marked with the circles. The other points are excluded from the fit because the correlation is dominated by resonance effects.

arising from Bose-Einstein statistics, but will not be free of all correlations; momentum conservation will push R up at large Q_{12}. The width of the peak at $Q_{12} - 0$ reflects the size of the source of the two bosons, *i.e.* large width in momentum space implies a small spatial source. The width of R in Fig. 1 corresponds to $r12 \approx 0.9\ fm$ for an exponential fit and is largely independent of Q^2.

Measurements with the CLAS detector at Jefferson Lab of two proton correlations have been performed on nuclear targets. Some of the results are shown in the left-hand panel of Fig. 2 [7]. The figure shows the effects on the source size r_{rms} of the average pair momentum ($p = |\vec{p}_1 + \vec{p}_2|/2$) and the nuclear size on the correlation function. At low average pair momentum r_{rms} increases for the heavier nuclear and approaches the nuclear size; implying the possible dominance of proton rescattering. The density of the source was extracted in Ref. [7] and found to be about 2-3 times the nuclear density in helium.

In the right-hand panel of Fig. 2 we show preliminary results from Jefferson Lab for the correlation function between $\pi^+\pi^+$ pairs on several nuclear targets [11]. Below $Q_{12} \approx 0.15$ GeV/c the correlations from heavy nuclei (lead and iron) continue to rise to a large positive correlation. The correlations from light nuclei (deuterium and carbon) reach a maximum and then drop. This drop at small Q_{12} may well be a product of an inefficiency for charged-particle tracks with small relative momentum and small average momentum [12]. Above $Q_{12} \approx 0.15$ GeV/c the correlation functions overlap one another within the statistical uncertainty.

Measurement of Bose-Einstein correlations at the EIC will provide a new portal to studies of high-density nuclear matter and the process of hadronization. The ground-state properties of nuclei are now well understood. *Ab initio* calculations of the nuclear ground state are successful for nuclei up to $A = 8$ and higher [13, 14] and lattice QCD calculations continue to make progress toward a fundamental understanding of the nucleon [15]. However, the high-density (and high-momentum) components of the nuclear ground state are only now being revealed. Short-range correlations have shown the importance of high-density components and the influence of the tensor force [16, 17]. The results of Ref. [7] (left-hand panel of Fig. 2) demonstrated the use of correlations to extract density information. Measurements at the EIC could also help us understanding neutron stars [18] and the EMC effect [19].

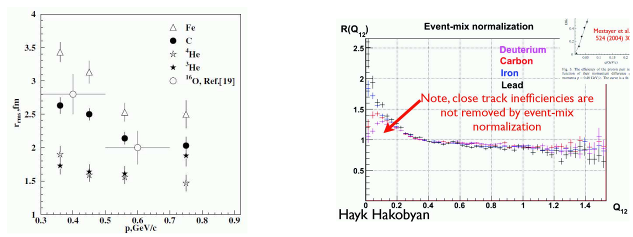

Figure 2: Left panel: The size parameter r_{rms} as a function of the mean pair momentum $p = |\vec{p}_1 + \vec{p}_2|/2$ is shown for different nuclear targets [7]. Data from Refs [8, 9, 10] are shown which correspond to $e - {}^{16}\mathrm{O}$ interactions at initial energy of 5 GeV and $Q^2 < 0.1(\mathrm{GeV/c})^2$ are shown for comparison. Right panel: Preliminary correlation functions for $\pi^+\pi^+$ from the CLAS detector at Jefferson Lab [11].

Hadronization and fragmentation (the formation of hadrons in hard scattering and the breaking of a QCD 'string') are fundamental processes described by QCD. Considerable data have been collected on these processes and the data have been parameterized and used as inputs to the analysis of high-energy data (*i.e.* the Large Hadron Collider (LHC)). However, the methods are *ad hoc* and there is no QCD-based, underlying theory to explain the data. Recent results from RHIC, HERMES, Jefferson Lab, and other facilities are starting to reveal the properties of quarks as they propagate through nuclear matter [20]. The atomic nucleus is used as a filter or analyzer to study the space-time properties of quarks moving through the medium and the formation of hadrons. Understanding these results and resolving questions like the competition between prehadron absorption and gluon radiation continue to be a challenge. A new era will open with the Jefferson Lab 12-GeV upgrade and later with the EIC. The higher luminosity will make multidimensional analysis accessible (Q^2, ν, z) along with new production channels (K, η, π^0) to probe the physics. As one moves to higher Q^2 the stretching of the QCD color string in the direction of propagation may become evident. Calculations of BECs in e^+e^- annihilation reveal that information about the string tension can be obtained even at low Q^2 where the source is roughly spherical [21].

We have simulated Bose-Einstein correlations for $\pi^+\pi^+$ pairs at the kinematics of the Electron-Ion Collider to investigate the feasibility of measuring BECs at the EIC. For our starting point we used the results for $\pi^+\pi^+$ correlations from ep reactions at DESY that are shown in Fig. 1 [3]. That measurement covered the range $Q^2 = 4 - 8000$ $(\mathrm{GeV/c})^2$ and there was limited Q^2 dependence in the BEC parameters they extracted. It is reasonable to believe those parameters may also apply to the EIC kinematics. We chose the $\pi^+\pi^+$ channel because we expect them to be abundant and there is data from other experiments that enable us to make comparisons. We took advantage of several existing tools to perform the simulations. The Pythia program was used to generate events [22]. The code creates multihadronic final states produced in interactions between two incoming particles with the objective to represent a wide range of strong interactions within and beyond the Standard Model. Within Pythia, the Lund model is used to simulate fragmentation and hadronization. There is also an option for independent fragmentation where the user has greater control over the processes. The program also includes a feature to simulate Bose-Einstein correlations [23, 24]. The algorithm for the BECs starts with the usual fragmentation simulation and then pairs of identical particles (*i.e.* $\pi^+\pi^+$) are selected. For these pairs the relative 4-momentum Q_{12} is modified according to the desired parameterization (see discussion of Eq. 2 above) with the constraint that the total 3-momentum of the pair remains the same in the center-of-mass (cm). The overall effect of applying the algorithm is to preserve momentum conservation, but reduce the energy. To compensate for the energy reduction, the cm momentum vectors are then rescaled.

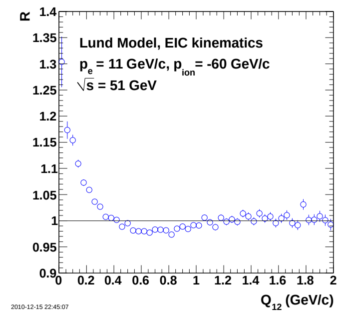

Figure 3: Pythia simulation of $\pi^+\pi^+$ Bose-Einstein correlations (BEC) at Electron-Ion Collider kinematics. BEC parameters were taken from Ref. [3]. The Lund fragmentation model was used.

We now discuss the results of our simulations. As a consistency check we compared the simulated correlation function R for $\pi^+\pi^+$ pairs with the measurements from DESY shown in Fig. 1. The simulated correlation was weaker than the measured one, $R(Q_{12} = 0) = 1.2$ (simulated) versus $R(Q_{12} = 0) = 1.38$ (measured), and not as wide, but still experimentally significant. Since we are studying the possibility of observing BECs these parameters from Ref. [3] will provide a more conservative (and safer) test. We also simulated the BECs at the same kinematics as the preliminary results from Jefferson Lab shown in the right-hand panel of Fig. 2 ($p_e = 5$ GeV and fixed target). Here we found the simulated correlation disappeared entirely. The multiplicity of the events generated by Pythia dropped significantly at these kinematics reflecting the limitations of the code at these lower energies. Since the EIC will run at energies lower than Ref. [3], but above the current ones at Jefferson Lab our estimates of the BECs are again conservative ones. Our simulation of R at EIC kinematics is shown in Fig. 3. There is, like the Ref. [3] data, a sizable correlation at $Q_{12} = 0$, a decrease in R with width ≈ 0.2 GeV/c, a dip below unity (recall discussion above of Fig. 1) and then the data approach one at high Q_{12}. The Lund model was used here for the fragmentation and a calculation using the independent fragmentation model in Pythia yielded similar results. We may expect sizable correlations functions at the EIC.

One of the possible effects we may see at the EIC is the stretching of the QCD color string at high Q^2 and/or changes in the string tension (recall Ref. [21]). The fragmentation region may not be spherical as observed in Ref. [21], but may have different sizes in the longitudinal and transverse directions. Such a difference was measured in Ref. [3] where the longitudinal radius was 0.26 ± 0.03 fm bigger than the transverse one. To search for such an effect in our simulation requires a different approach to extracting R. We worked in the longitudinal Center-of-Mass System (LCMS) where the longitudinal components of the pair momentum add to zero and extracted the transverse and longitudinal 3-momentum differences Δp. The BEC parameterization is still symmetric in Q_{12} in the cm. Our initial results are shown in the left-hand panel of Fig 4. We used the BEC parameters from Ref. [3] at EIC kinematics ($p_e = 11$ GeV/c, $p_{ion} = -60$ GeV/c, $\sqrt{s} = 51$ GeV). The transverse (red, filled circles) and longitudinal (blue, open circles) produce the characteristic shapes seen above for R, but with significant quantitative differences between the two. The transverse correlation is about twice the longitudinal one at $Q_{12} = 0$ and the widths are similar. The large difference between the correlations functions suggests this may be a useful tool for studying space-time properties of the emission source. To delve deeper into this question, we considered the sensitivity of the LT distributions to changes in the size parameter in the BEC parameterization. The middle and right-hand panels in Fig. 4 show a comparison of the same LT correlation functions shown in the left-hand panel with ones calculated with a smaller size parameter ($r_{12} = 0.73$ fm versus $r_{12} = 0.93$ fm from Ref. [3]). The smaller radius amplifies the shape of the correlation functions (the maximum at $Q_{12} = 0$

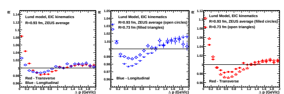

Figure 4: Longitudinal and transverse (LT) correlation functions calculated with Pythia. The left-hand panel shows the correlations functions using the Ref. [3] parameters. The other two panels show a comparison between those results and ones from a calculation with a smaller source size r_{12}.

increases and the dip at $Q_{12} \approx 0.6$ GeV/c is deeper. We can clearly separate the two distributions within the Monte Carlo statistics shown here. We expect the statistical uncertainties for an EIC measurement to be better than the Monte Carlo statistical uncertainties shown here. The cross sections for these reactions (from Pythia) multiplied by the EIC luminosity suggests a production rate of 10^5 Hz. We also fitted the correlation functions with Eq. 2 and obtained uncertainties on the size parameter r_{12} less than 0.15 fm which is comparable to the precision of the results in Ref. [3]. Thus, we will be able to discriminate between different size parameters at least at the 0.2 fm level.

Bose-Einstein correlations will be an important tool at the Electron-Ion Collider for studying high-density nuclear matter, the dynamics of the QCD string in hard scattering, and to gain a deeper understanding of fragmentation and hadronization. Our simulations have shown us that we can expect large (20%) effects in the correlation function at small Q_{12}. The longitudinal-transverse correlations are sensitive to the size parameter to a fraction of a fm. Finally, the large $\pi^+\pi^+$ BECs observed at JLab that are not reproduced in our simulations hold the promise of new physics to uncover with the EIC.

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